Lessons Learned from a Lady
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Lessons Learned From a Lady

I. Peterson

The recent Statue of Liberty restoration provided some unique research opportunities

By IVARS PETERSON

The Statue of Liberty's iron ribs were rusty. Thick oxide crusts had thrust open the bands holding parts of her copper skin in place. During heavy rainstorms, water dripped freely into the leaky statue's interior. Nearly a century of human use, moisture, salt-laden air and contact between iron and copper had taken their toll.

Now, after its centennial restoration, the statue stands as a monumental, 100-year "field test" that has a lot to tell us about how materials and systems perform, says Hugh C. Miller, chief historical architect at the National Park Service (NPS) in Washington, D.C. "The knowledge gained in analyzing existing conditions and finding solutions to repair, rehabilitate or restore the statue may be directly applicable to building preservation [and] maintenance . . . for all types of structures," he says. "We may even learn how to build better."

To help preserve the lessons learned during the Statue of Liberty restoration, which was completed this year, some 30 specialists who had been deeply involved in the project recently met in New York City to describe their roles and accomplishments. The conference sponsors, NPS and the Houston-based National Association of Corrosion Engineers, plan to publish the information presented at the meeting as a guide for future preservation efforts.

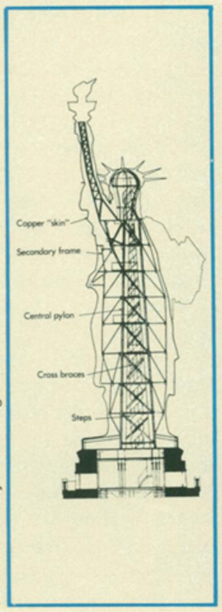
The Statue of Liberty, as envisioned by sculptor Frédéric-Auguste Bartholdi and engineer Alexandre-Gustave Eiffel, combines ancient materials with an innovative structure. At the statue's core stands a rigid iron tower with a secondary framework that reaches out to a shell of copper sheets. These sheets, riveted together, hang from a complex system of supporting iron bars attached to the framework. This arrangement allows the statue's copper skin to "breathe" by shifting or sliding independently along its iron grid, while the pull of gravity or the force of a blowing wind is still effectively transferred from the skin to the main structure.

Eiffel recognized that galvanic corrosion – the electrochemical reaction between two dissimilar metals – would be one of the greatest hazards facing Liberty in her marine environment. In the presence of moisture, the combination of iron and copper would act like a battery, and the iron would rapidly rust and eventually disintegrate.

Eiffel tried to solve the problem by inserting an insulating layer of asbestos between the iron ribs and the copper skin. But his solution was ineffective. Because copper is such a good electrical conductor, even a single contact point with iron is enough to spoil the insulating effect. The iron armature system ended up rusting so badly that all the bars had to be replaced during the restoration.

The presence of copper sulfate may have contributed to this corrosion process, says metallurgist Norman Nielsen, a consultant in Wilmington, Del. His tests showed traces of copper and sulfur on the rusted armature bars. "If you pass water containing dissolved copper over iron or steel," he says, "you're going to accelerate markedly the rust corrosion process."

Choosing a suitable replacement material for the iron bars was no simple matter. Iron, like the "puddled" wrought iron of the original bars, would merely rust away again. Copper was a natural substitute, but to match the strength of iron, each bar would have to be heavier and thicker. Other, more promising choices



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In Eiffel's innovative design, a central pylon with a secondary framework reaches out to the Statue of Liberty's copper skin (left). The copper sheets are attached to iron ribs (right) in such a way that the skin is free to shift slightly. Because of corrosion, the ribs had to be replaced with new stainless steel bars that were shaped to match the contours of the old bars (center).

Facing page: A life-size copy of the Statue of Liberty's copper face, as it would appear without its green patina, is now on display at the statue's base.

included copper-plated alloys and various stainless steels. NPS initiated a series of tests to determine which alloys would be most suitable as partners for copper.

In the end, two were chosen. One was ferallium, a high-strength, steel-aluminum alloy used by the British Navy as a bronze substitute. However, because this alloy tends to be springy, metalworkers have difficulty bending it into shape. It was used only for the flexible flat bars that connected the ribs to the iron framework. The alternative, 316L stainless steel, is easier to shape and was used for the armature bars themselves.

But that didn't end the problems. The 1,800 armature bars looked like "giant Chinese noodles," says Milton Einbinder of NAB Construction Corp. in College Point, N.Y. Each bar, with its intricate twists, bevels and turns, had to be shaped individually. This shaping made some parts of the bars brittle – a process called work hardening. To restore their flexibility, all the bars had to be annealed by heating, and then rapidly cooling, them. Unfortunately, when that was done, the stainless steel lost its corrosion-resisting surface film.

Developing procedures for annealing the steel bars and restoring their corrosion resistance took several months. "At the time we let the contract," says Einbinder, "we didn't know how to do it."

Annealing was done by passing 30,000 amperes of electric current through each bar for about four or five minutes, using, when the machine was on, almost all of the power supplied to Liberty Island. The heat generated was tremendous, says Einbinder. "It felt like you were in a toaster oven." After heating, each bar was dunked in a trough of water. Restoring corrosion resistance involved cleaning and bathing the bars in nitric acid. Altogether, almost three miles of steel had to be treated in this way.

Backing tape, consisting of a glass-fiber web coated with Teflon, replaced the asbestos liner between the copper and stainless steel. The tape not only reduces the chance of galvanic corrosion occurring but also works as a lubricant. It allows Liberty's copper skin to slide across the stainless steel without sticking when the statue expands and contracts due to temperature changes during the day.

"If the environment changes in the future – and we don't know what's going to happen in the next 100 years – that Teflon isolator could be very important," says corrosion scientist Robert Baboian of Texas Instruments, Inc., in Attleboro, Mass. Results of tests at his laboratory show that without such an isolator, corrosion could occur if the steel-copper combination were ever immersed in water for a lengthy period.

Engineers were similarly concerned about the state of the iron in the statue's central pylon. Constant bending, twisting and other stresses may have caused metal fatigue and weakened the structure.

Puddled iron – the material used by Bartholdi and Eiffel – is relatively soft and contains a high proportion of slag inclusions, silica fragments and other impurities. Its layered structure gives it a fibrous or wood-grain appearance.

Tests at Lehigh University in Bethlehem, Pa., and at the Centre des Etudes Techniques des Industries Métallurgiques in Paris showed that the iron has the same impact resistance as most modern steels. The inclusions, rather than weakening the metal, inhibit crack growth by redirecting the cracks. "In this fashion," says engineer Pasquale DiNapoli of Ammann & Whitney, Inc., in New York City, "the material is able to absorb very high levels of energy." He adds, "From a fatigue viewpoint, we can project that the statue would last indefinitely."

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The Statue of Liberty's original torch and flame, shown here, had to be replaced because of extensive corrosion damage. Holes cut into the copper flame to create windows allowed moisture to leak into the statue's arm. The original torch is on display in the museum.

Restorers also had to undo earlier, unsuccessful efforts designed to waterproof and protect the statue's interior from corrosion and other damage. That meant safely and carefully removing up to six layers of various lead-based and vinyl paints and an underlying coat of coal tar from both the thin, soft copper sheets and the iron framework.

After a series of small-scale tests at the Statue of Liberty, NPS decided that the iron could be cleaned by blasting those surfaces with an aluminum oxide powder. That method, however, could not be used on the copper sheets because of possible damage to the copper.

NPS personnel considered using softer abrasives such as walnut shells, glass beads and ground corncob, but most of these materials couldn't cut through the topmost vinyl layer. Another possibility, the use of hot air or steam, would probably mar the statue's exterior by softening the coal tar enough to let it ooze through joints and other breaks in the surface. Chemical removers either took a long time to penetrate all the layers or were flammable and generated toxic fumes.

Eventually, liquid nitrogen was chosen as the removal agent. "Although there are references to such supercooling techniques in the coatings-removal literature," says Frances Gale, formerly with NPS and now with ProSoCo, Inc., in Kansas City, Kan., "the use of liquid nitrogen in large-scale coating removal is somewhat innovative." Liquid nitrogen producers and their customers usually regard this particular property as a nuisance or a maintenance problem.

The scheme worked. The extreme cold caused the paint layers to shrink and crack. Large paint flakes readily dropped away from the copper. It took only three weeks to remove all the paint from 11,000 square feet of interior surface. However, despite being exposed to extreme cold, most of the coal tar remained.

Coal tar removal required "a gentle approach for a tough problem," says Victor Strauss of Ben Strauss Industries, Inc., in Long Island City, N. Y. "In order to overcome these obstacles, two items were necessary: a new sandblasting tool and a gentle yet effective cleaning material."

Strauss came up with a small, portable tool that could sandblast and vacuum simultaneously. "Basically, what we did was install a sandblasting nozzle inside a vacuum cleaner," he says. "It would allow the blasting material to enter from one end and at the same time vacuum it out the other end."

To find the right blasting material, Strauss tried out a wide range of substances, including cherry pits, plastic beads, salt, rice and even sugar. "They were all unsatisfactory," he says, "either too abrasive or too mild." Finally, he thought of trying baking soda (sodium bicarbonate), which museum curators sometimes use for polishing dinosaur bones and some people use for brushing their teeth.

The baking soda's mild abrasive action successfully stripped off the coal tar. But there were two unforeseen problems. Because baking soda absorbs moisture from

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While the restoration was going on, a special aluminum scaffolding enveloped the statue.

the air, dehumidifiers had to be installed at the compressor pumping air to the blasting tools to keep the tools from clogging. Furthermore, a small amount of baking soda leaked outside through cracks now opened by the coal tar removal. When a light rain fell, sections of the statue's green outer skin turned bright blue. Apparently, the bicarbonate had reacted with the copper's green patina to form a carbonate. Workers were then stationed on the scaffolding surrounding the statue to wash away immediately any baking soda that leaked through.

"There are still stains on her skin, especially on the left cheek," says Baboian. "We don't know whether that's going to have a lasting appearance effect." Most of the carbonate has been washed away, he says, but its effect on the patina left behind is yet unclear.

To complete the job, seams between the 300 copper sheets were carefully cleaned and then closed with a silicone sealant. The sheets themselves, except in the area of the head, were left uncoated. The interior structural iron was covered with a special, inorganic-zinc coating originally developed by NASA. In effect, that laid down a layer of zinc, which would help protect the underlying iron from corrosion. Then a chemical-, abrasion- and graffiti-resistant epoxy paint was applied as a topcoat.

It took dozens of tests to find the right combination of coatings and sealants, says Greg Smyth of GSGSB Architects Engineers Planners in New York City. "Care was taken not to introduce substances which could detrimentally affect the statue."

Viewed from a distance, the Statue of Liberty appears to wear a uniformly green coat. Her copper skin, originally the dull brown color of an old penny, has, over the years, weathered to a powdery green color. A closer look, however, reveals darkened areas, stains and some brightly colored streaks.

Liberty's green patina is the result of a complex chemical process that researchers are just beginning to understand. In this form of corrosion, copper and atmospheric gases like sulfur dioxide and hydrogen sulfide combine in the presence of water to produce a thin surface film.

By measuring the thickness of the copper under and then adjacent to some patches where coal tar, applied decades ago, had seeped through, researchers were able to estimate how quickly the copper is corroding. "According to our measurements," says Baboian, "around 5 percent of the thickness of the copper has been lost over the last 100 years." This agrees with the measured corrosion rate for copper in similar environments throughout the world, he says.

The statue's corrosion layers, in fact, protect her from further decay. To avoid disturbing this protective patina, NPS and its advisers decided to carefully scrape away only those stains and masses of bird droppings that affected her appearance most. The rest of Liberty's surface was simply washed with water and left as it was.

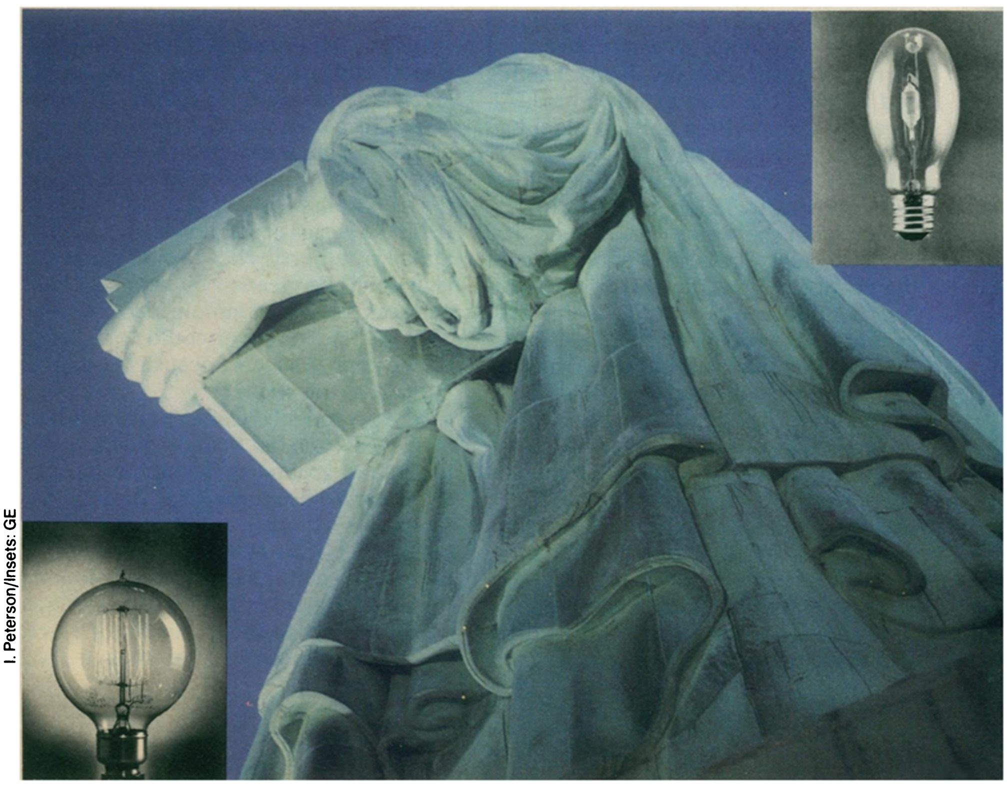
However, sections of the patina itself may be changing. Large areas on the left side of the statue's surface appear to be getting darker, as if the green patina were washing away to reveal the black oxide and sulfide layer underneath. Baboian blames the effect on acid deposition and the severe weather patterns that come from the northeast (SN: 6/29/85, p.404). Other researchers contend that fine, wind-blown sand may be the culprit. Most of the change seems to have occurred since 1965.

X-ray diffraction studies show that the green patina consists largely of two basic copper sulfates: brochantite, $CuSO_4 \cdot 3Cu(OH)_2$, and antlerite, $CuSO_4 \cdot 2Cu(OH)_2$. With a slightly different composition and crystal structure, antlerite dissolves more readily in water and is more susceptible to wind erosion than brochantite. Moreover, an increase in the acidity of surrounding moisture may convert stable brochantite into less stable antlerite.

Baboian suggests that acid rain could be causing that kind of transformation. As a result, this antlerite-loaded green patina may be washing away, especially in areas exposed to the prevailing winds.

"We took samples of the patina throughout the statue," he says. "One of the interesting effects we saw was that in darkening areas, the green patina had a high antlerite content." Furthermore, other measurements show that the patina is about 10 times thicker in greenish areas than in darker areas.

"This finding and other patina analyses



The new Statue of Liberty lighting scheme is designed to capture the quality of natural daylight. Researchers had to invent two new metal-halide lamps (upper right) to provide the right colors. The original 1916 lighting scheme used 246 bulbs (lower left); the new one uses only 42.

I. Peterson/Insets: GE

in recent years suggest that the copper of the Statue of Liberty may be suffering, or will suffer, atmospheric corrosion at higher rates than was the situation one or two generations ago," says Nielsen. Examination of several pieces from the torch shows that the patina there is very porous, coarse and granular. In small regions, it is completely gone, exposing bare copper metal.

In contrast, the patina on a sample removed from the torch in 1905 and stored at the National Archives in Washington, D.C., is dark green — almost black — in color, dense, brittle and uniform in thickness. It consists mainly of brochantite and a basic copper chloride called atacamite, $CuCl_2 \cdot 3Cu(OH)_2$. The chloride is concentrated at the copper-patina interface, indicating that rain washes it away relatively easily. This accounts for why chlorides are not commonly found on most surfaces of the statue today.

"The appearance of the statue will continue to show change over the lifetime of the copper, perhaps several hundred years," says Nielsen. "It will be interesting to determine and observe in future years how the distribution of [colors] . . . might change."

Curiously, at least one copper sheet, located on the statue's torch-bearing arm, is staying green while its neighbors are darkening. "It must have something to do with the metallurgy of the copper," says Baboian. The unaffected copper seems to be much softer and purer than the darkening copper, he says. Samples from the darkening copper sheets contain large clumps of copper oxide.

That doesn't appear to affect the copper's corrosion rate, says Baboian, but it may affect the copper's surface properties. "A more stable patina forms on the purer copper," he says, "which explains why the panel on the left side of the torch arm has retained its green appearance."

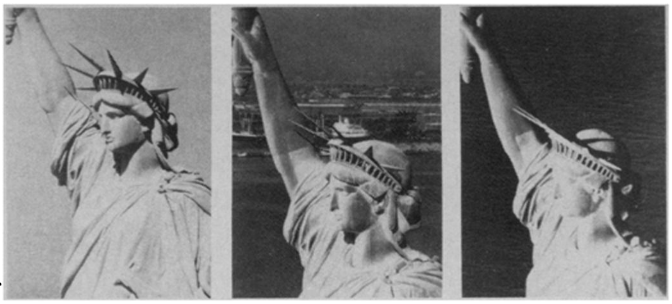
John P. Franey of AT&T Bell Laboratories in Murray Hill, N.J., has also examined samples from the two types of copper sheets, and he comes to a somewhat different conclusion. "We find no elements in one sheet that we don't find in the other," says Franey. "The real difference lies in the grain structure, and that is totally different."

Although Franey's micrographs show a difference in the size and number of copper oxide inclusions, they also hint that the lighter copper sheet may have been heated after being pounded into shape. The darker sheet, like most others on the statue, went through no such heat treatment. The reason why the stable sheet had been heat-treated has disappeared with the workmen who originally fashioned the statue.

In addition, Franey and his colleague Thomas E. Graedel have been looking closely at the chemistry of patina formation. They postulate that, initially, a thin, fragmented layer of copper oxide forms

The Statue of Liberty's left side has been getting darker, as shown in these photos taken in 1965 (left), 1974 (center) and 1983 (right). One copper plate on the arm seems to be resisting this change.

Jay Maisel



on the copper metal's surface. Then, when the surface is wet, copper ions migrate through this layer and react with sulfate ions from the atmosphere to form the upper layer of crystalline brochantite. The processes that cement these crystals into place probably involve organic compounds, which also settle on the surface. Analyses of the patina show that it does, in fact, contain traces of formate, acetate, oxalate and carbonate species.

Graedel and Franey analyzed seven patina samples from the statue and eight from copper roofs at the Murray Hill laboratories. "That let us look at copper samples in the same geographic region that had been exposed for periods from one to 100 years," says Graedel. "By knowing something about the atmosphere and something about the analyses on all these pieces of copper, we've made what I think is the first decent, extensive coupling of the atmosphere in which the patina has grown to the chemical characteristics that we find on the patina."

With a better idea of which factors affect the rate of patina formation, Graedel and Franey conclude that "the time required for the green patina to form has decreased from about 20 years in the late 19th century to about eight years today." As the patina forms in a continual process of erosion and renewal, the researchers say, more of it sticks now than in the past because of the greater abundance of organic pollutants that help cement the patina together.

One offshoot of Franey's research has been the development of a natural patination process that quickly gives shiny copper sheets a weathered, green look. Franey starts with a sheet of weathered copper. By applying the solvent acetone and lightly scraping with an abrasive pad, he causes the green patina to fall off in small flakes. This material can then be reapplied to bare copper. "It's a transplant of the patina," says Franey. "It takes about one to three weeks for the organics in the atmosphere to recement it to the surface."

Franey's patination process was used to cover about 30 square feet of bared or damaged copper surface where Liberty's robe meets her base. The new patina appears to be attached permanently, he says. That isn't true of the artificial patina that French artisans applied to the reconstructed torch. The torch's artificial green coat lasted only a few months before it was worn away by wind and rain, leaving behind a blackened, bare copper surface.

Lighting up the statue at night to do justice to its green patina was another problem. "In looking at the statue," says Howard Brandston of Howard Brandston Lighting Design, Inc., in New York City, "it became clear that she looked best in the early morning light." But no existing lamps would achieve this effect for a green figure. Brandston turned to the General Electric Co. in Cleveland, which invented two metal-halide lamps specifically for lighting the statue.

The new lamps have, as nearly as possible, says Brandston, "the quality of natural daylight, which contains warm light from the sun for highlights and cool light from the blue sky to fill in the shadows."

Each lamp, carrying a mixture of metals and a halogen such as iodine to get the right color, provides a compact source of high-intensity light at only 250 watts. Forty-two of these lamps supply more light than the 246 250-watt lamps originally used to light the statue. That's done by generating a lot of heat in a small space within each bulb, where the temperature can reach 9,000°F, higher than the melting point of iron. "This little thing is powerful," says Brandston.

The lamps also required a new electronic ballast to provide the high-voltage jolt needed to get them started. And General Electric researchers came up with new fixtures that have a highly reflective aluminum backing to keep the light beams narrow and focused.

Says Brandston, "Our basic goal was simply to make the statue look good."

The Statue of Liberty restoration was completed this year at a cost of $75 million. According to NPS, it was one of the largest, most comprehensive restorations ever undertaken. The statue's condition, says F. Ross Holland of the Statue of Liberty-Ellis Island Foundation in New York City, is now better than it has ever been.

The Statue of Liberty restoration afforded participants a chance to study in detail the history and state of a structure, says Miller, and to use that information to do a better restoration job. "This is the real lesson to learn from the Statue of Liberty," he says. "The transfer of information developed by this project not only will help in solving technical problems for other existing structures but also can establish a new 'whole-building' process of thinking." □